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Title: Neutrinos and the Dark Sector

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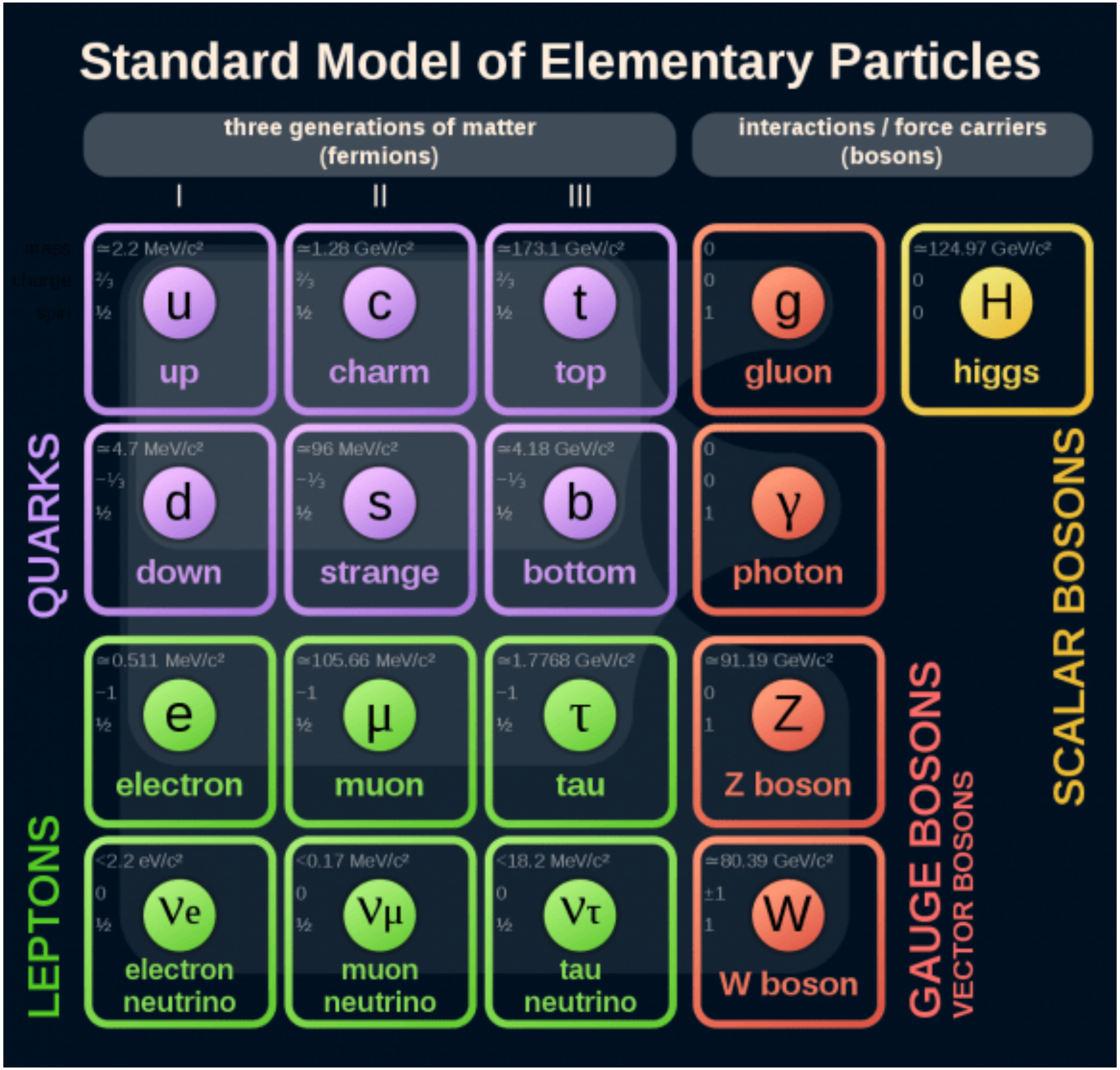
Neutrinos & the Dark Sector

W. C. Louis, LANL

January 21, 2021

- Neutrino Properties
- Short Baseline Neutrino Anomalies
- Dark Sector Models
- SBN Project at Fermilab
- CCM Experiment at Lujan
- Conclusion



The Standard Model makes up only ~5% of the mass-energy of the universe!

The dark sector (dark matter & dark energy) makes up ~95% of the mass-energy of the universe!

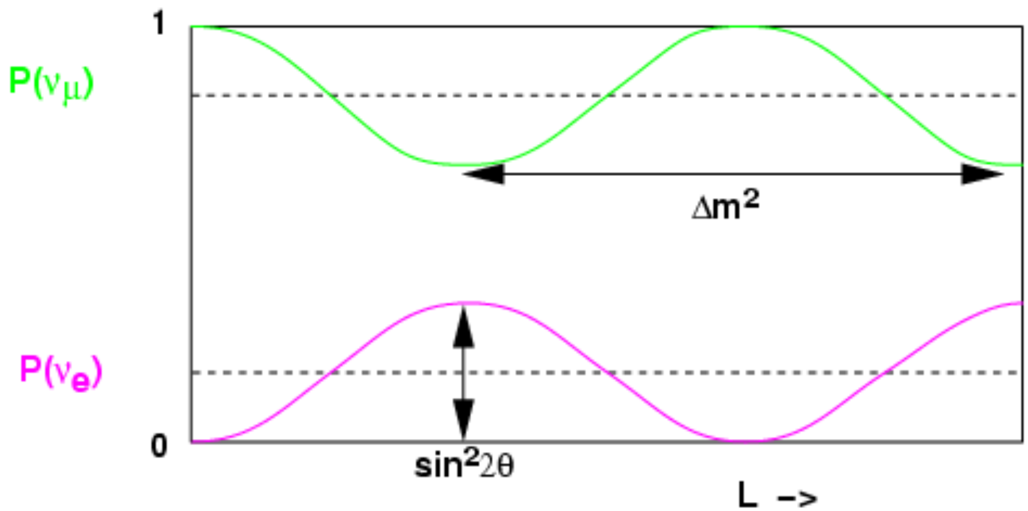
Are neutrinos the portal to the dark sector?

Salient Features of Neutrinos

- Neutrinos are neutral, spin ½, point-like particles with small, non-zero masses (< ~1 eV)
- Neutrinos interact very weakly with matter
- Neutrinos & photons dominate the universe in terms of number of particles
- Neutrinos undergo oscillations

Neutrino Oscillations

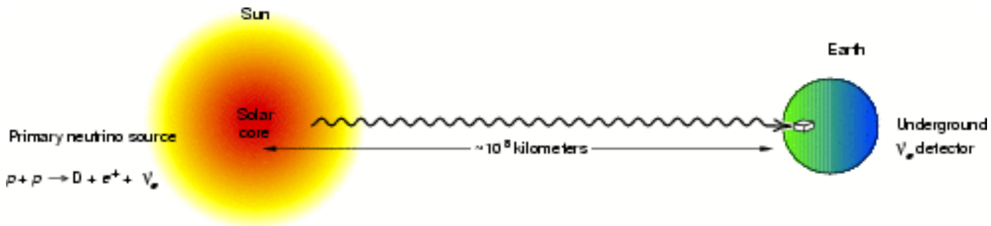
Weak Eigenstates		Eigenstates of Propagation
ν_μ	=	$\cos\Theta\,\nu_1 + \sin\Theta\,\nu_2$
ν_e	=	$-\sin\Theta\,\nu_1 + \cos\Theta\,\nu_2$



$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\ \Delta m^2\ L/E_\nu)$$

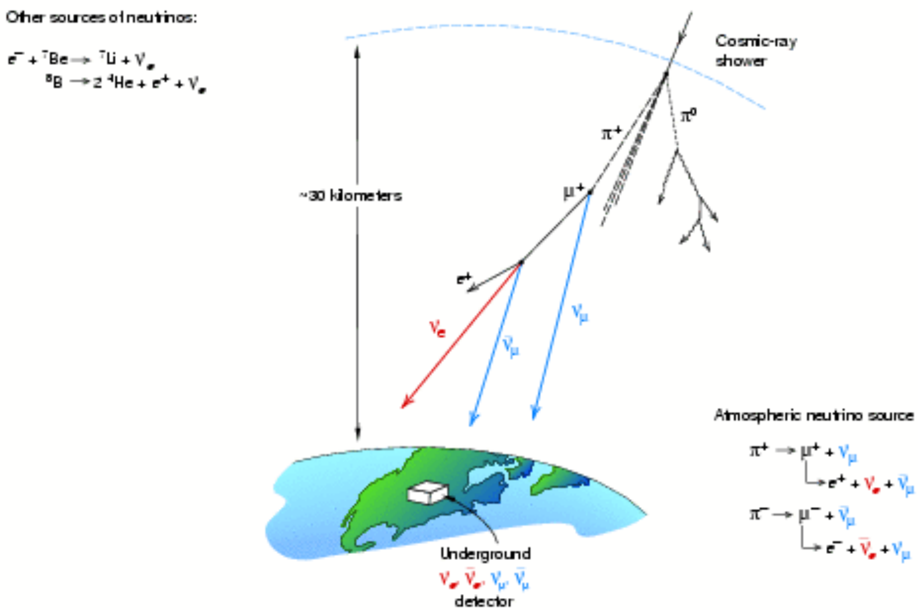
$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

Observation of ν Oscillations



SuperK, SNO, KamLAND, BOREXINO

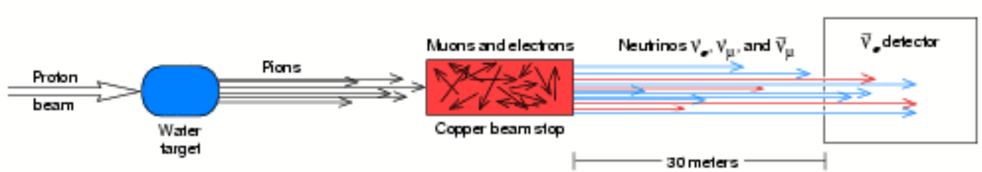
$\Delta m^2 \sim 0.00007 \text{ eV}^2$



SuperK, K2K, MINOS, OPERA, T2K, Double Chooz, Daya Bay, RENO, NOvA

$\Delta m^2 \sim 0.002 \text{ eV}^2$

2015 Nobel Prize for SuperK & SNO!



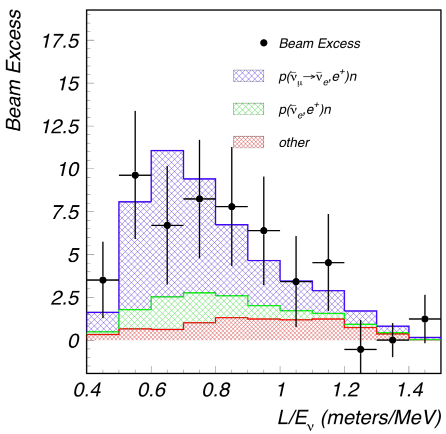
LSND, MiniBooNE, Reactor ν, Gallium Anomaly

$\Delta m^2 \sim 1 \text{ eV}^2$

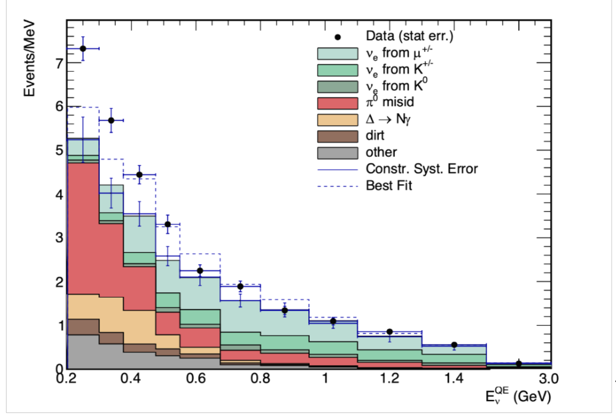
Short-Baseline Neutrino Anomalies

$\nu_\mu \rightarrow \nu_e$ Appearance

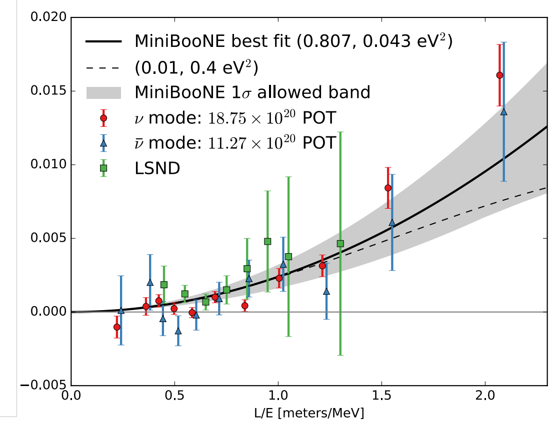
LSND



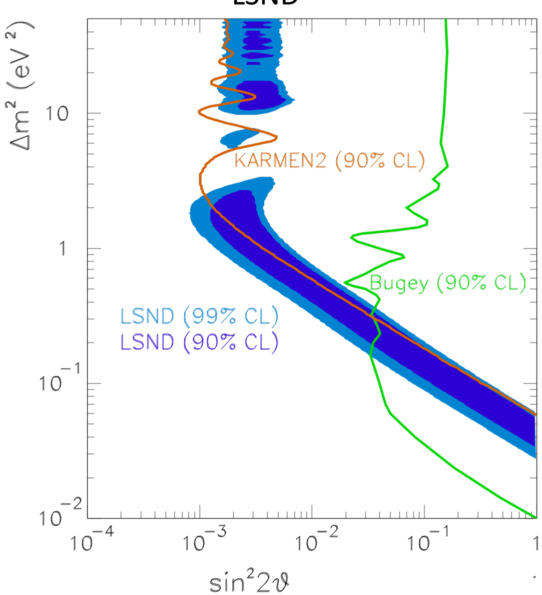
New MiniBooNE Neutrino



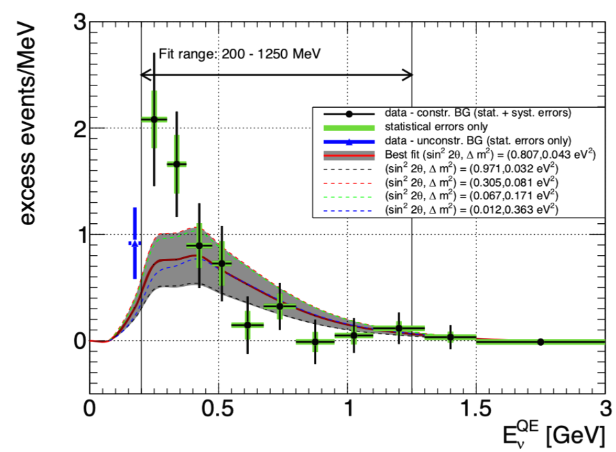
New MiniBooNE Neutrino & Antineutrino



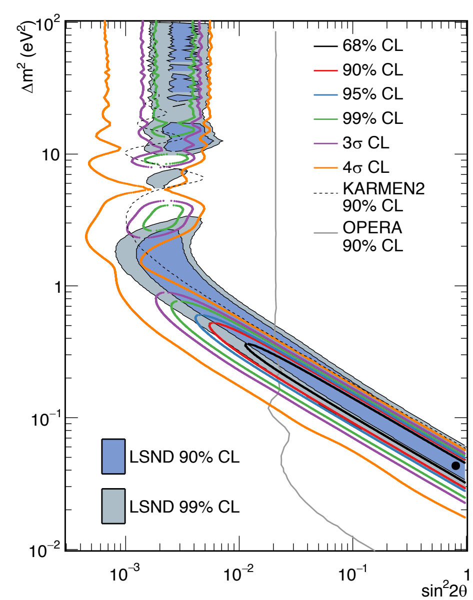
LSND



New MiniBooNE Neutrino



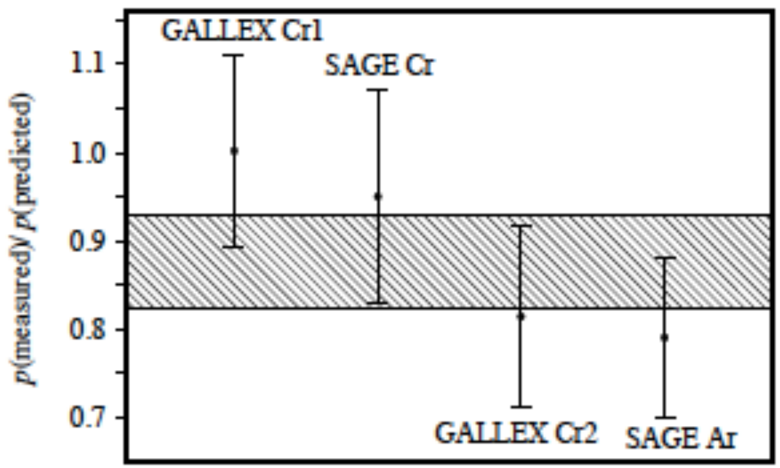
New MiniBooNE Neutrino + Antineutrino



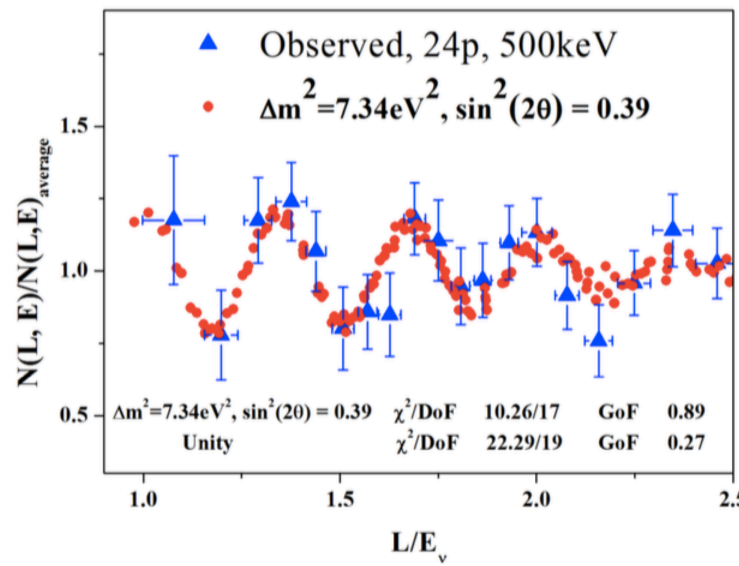
Short-Baseline Neutrino Anomalies

ν_μ & ν_e Disappearance

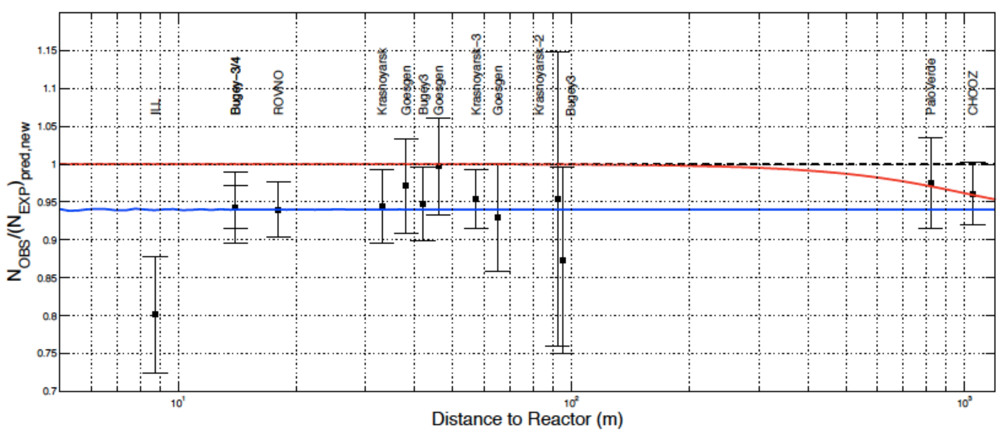
Gallium Anomaly



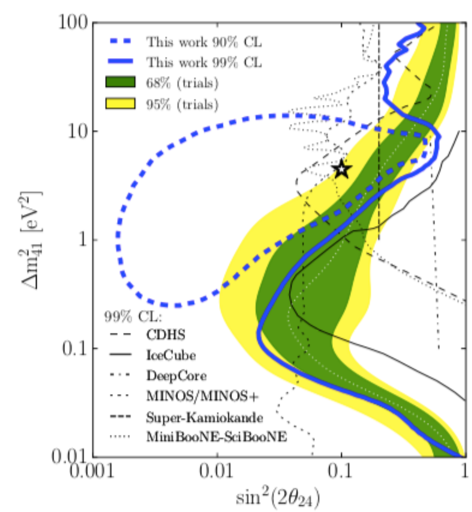
Neutrino-4 Reactor Experiment



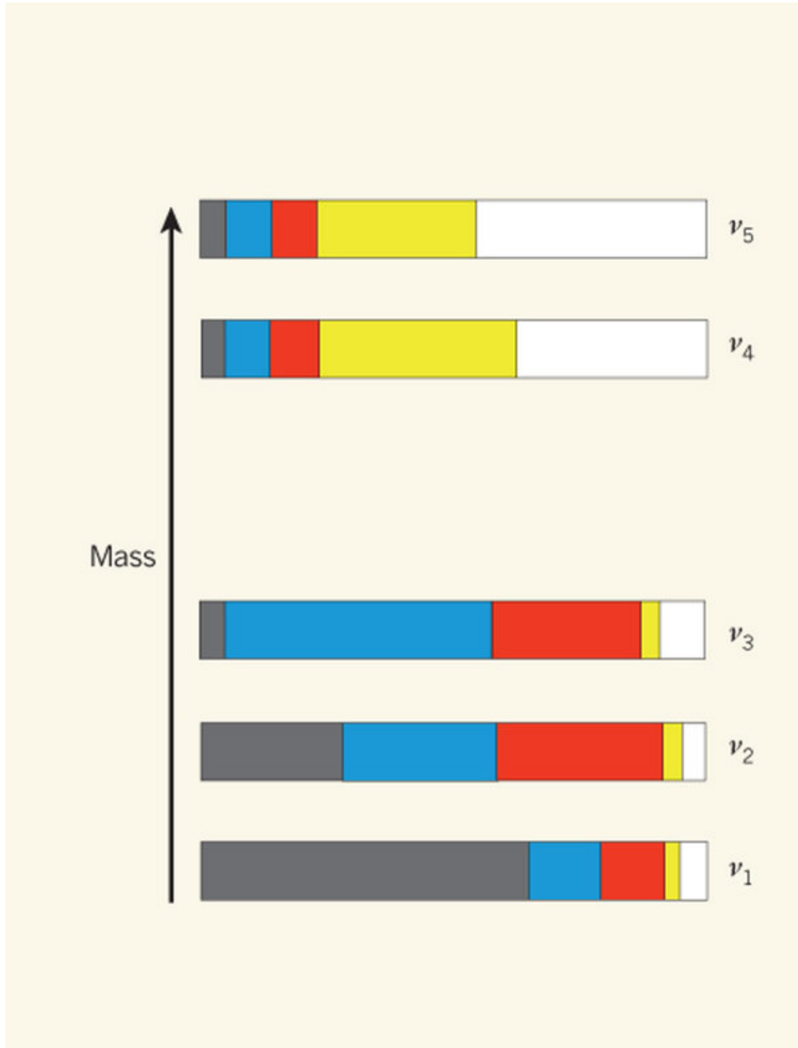
Reactor Neutrino Anomaly



IceCube Experiment



3+N Sterile Neutrino Models



3+N Models with Dark Sector Particles Can Explain the World Data

(Sterile neutrinos with new mediators, interactions, and scalar particles!)

- Sterile Neutrino Decay
- Sterile Neutrinos with Resonant Oscillations
- Sterile Neutrino NSI & New Gauge Bosons
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Lorentz Violation & CPT Violation
- Extra Dimensions (active neutrinos are stuck on the brane, while sterile neutrinos can propagate in the bulk)
- Mass-Varying Neutrinos
- Neutrino Decoherence
- etc.

A two-Higgs doublet solution to the LSND, MiniBooNE and muon g – 2 anomalies

Waleed Abdallah, Raj Gandhi, and Samiran Roy

arXiv:2010.06159

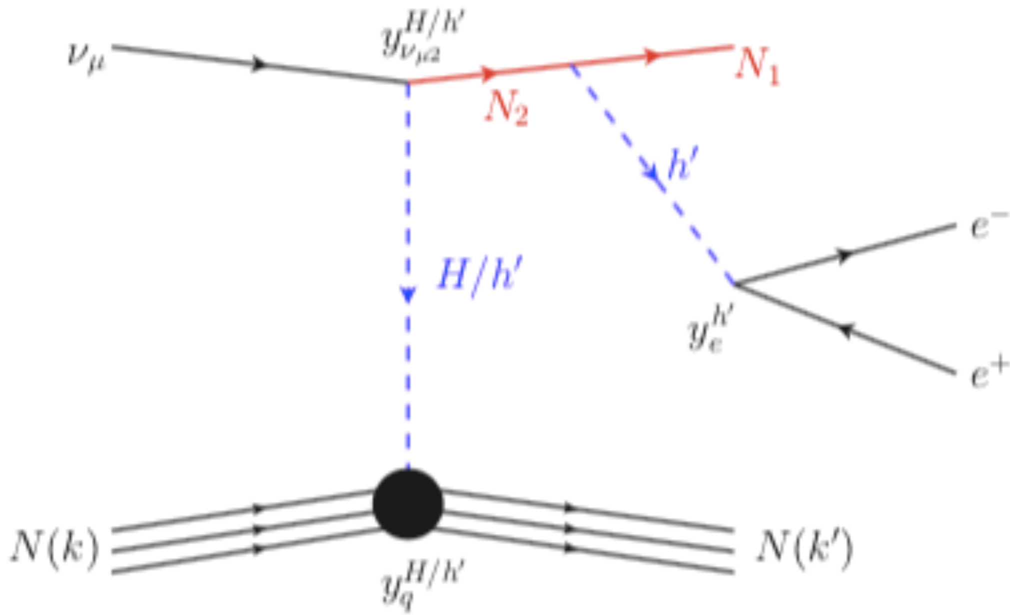


FIG. 1: Feynman diagram of the scattering process in our model which leads to the excess in LSND and MB.

A two-Higgs doublet solution to the LSND, MiniBooNE and muon g – 2 anomalies

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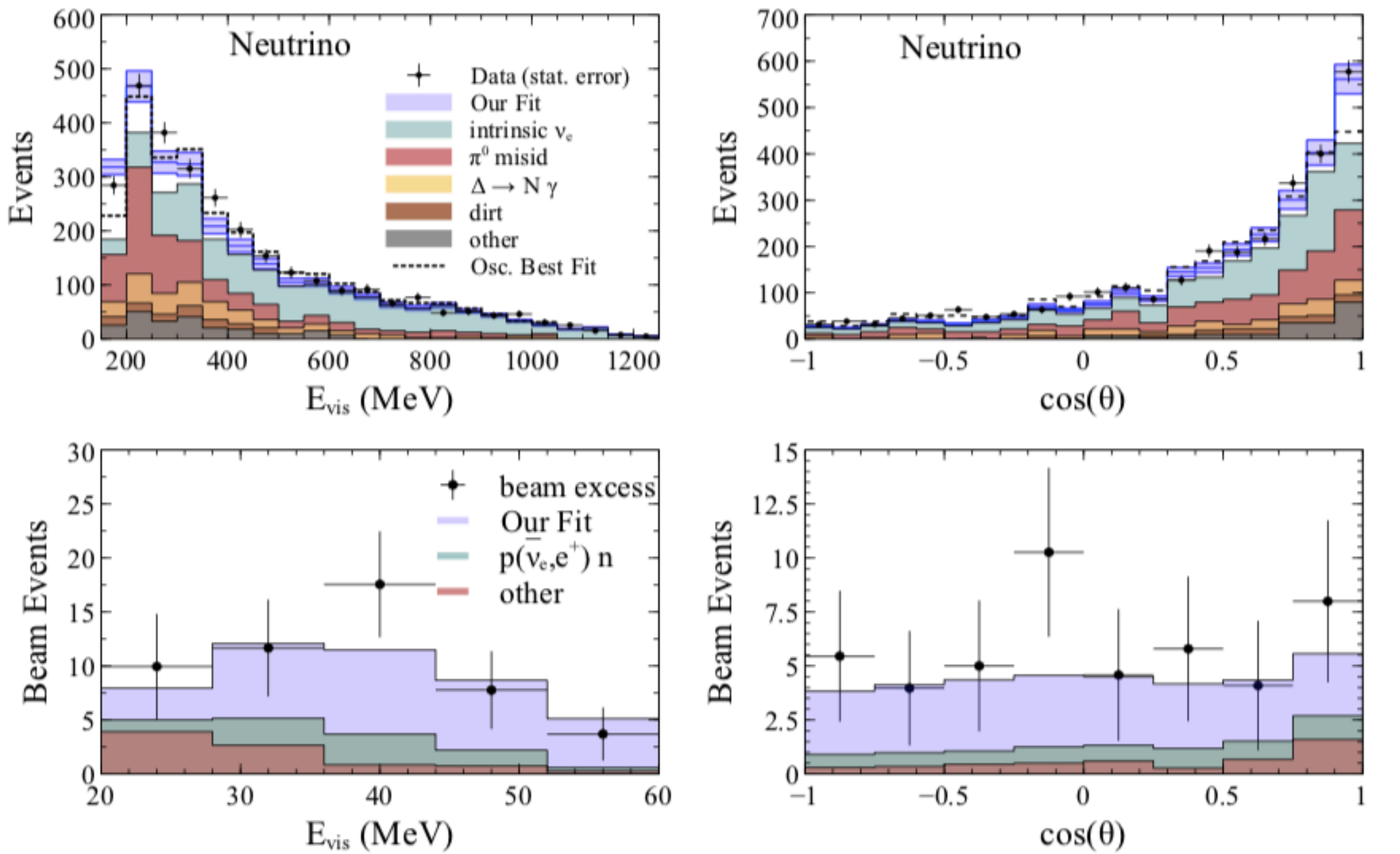
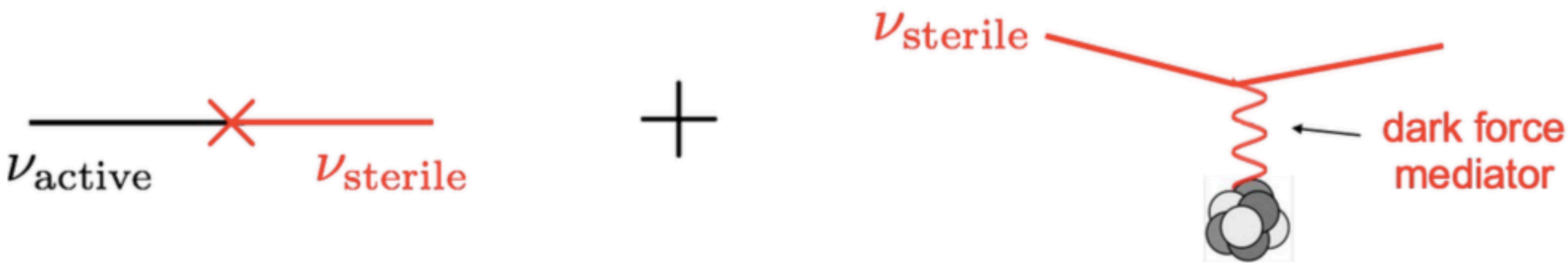


Neutrinos & the Dark Sector

(Daniele Alves & Patrick deNiverville)

- Recent theoretical effort initiated at LANL: implications of dark sectors to neutrino phenomenology beyond the Standard Model

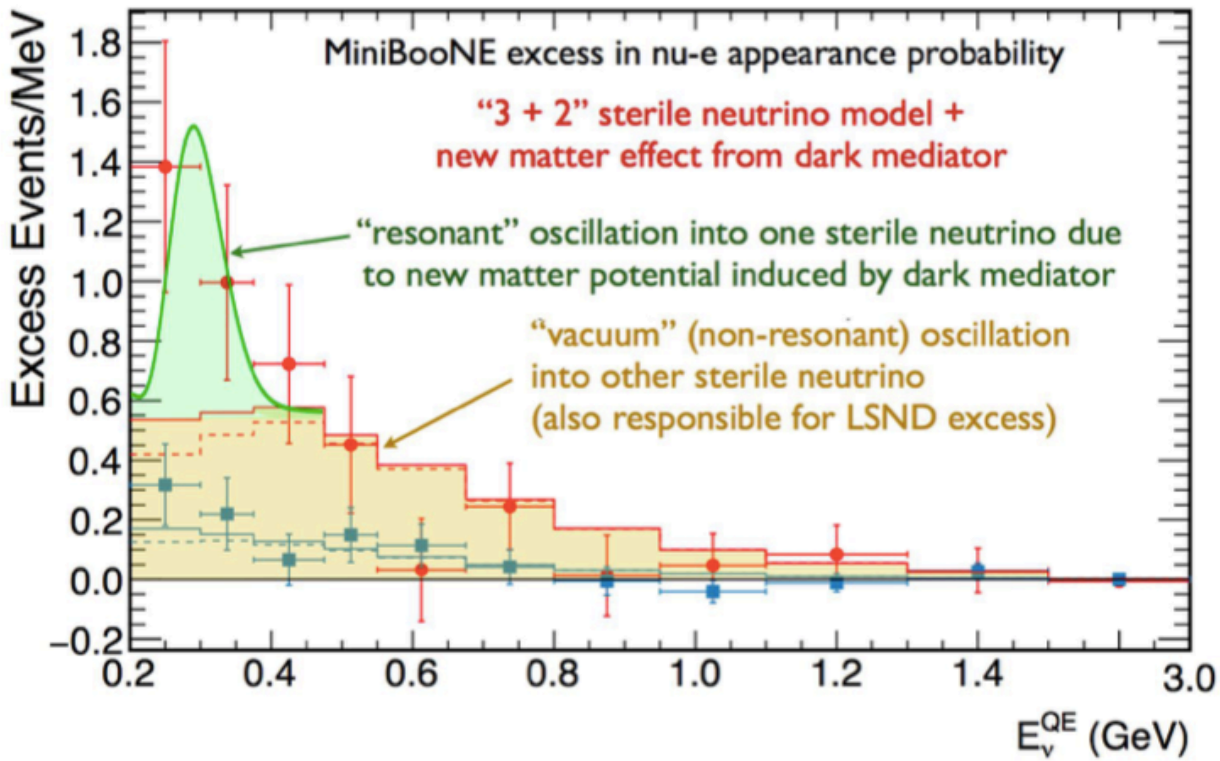


- Under generic assumptions above, neutrino oscillations in medium should be modified by *new matter effects*

(D.S.M. Alves, P. deNiverville, W. Louis, ***in preparation***).

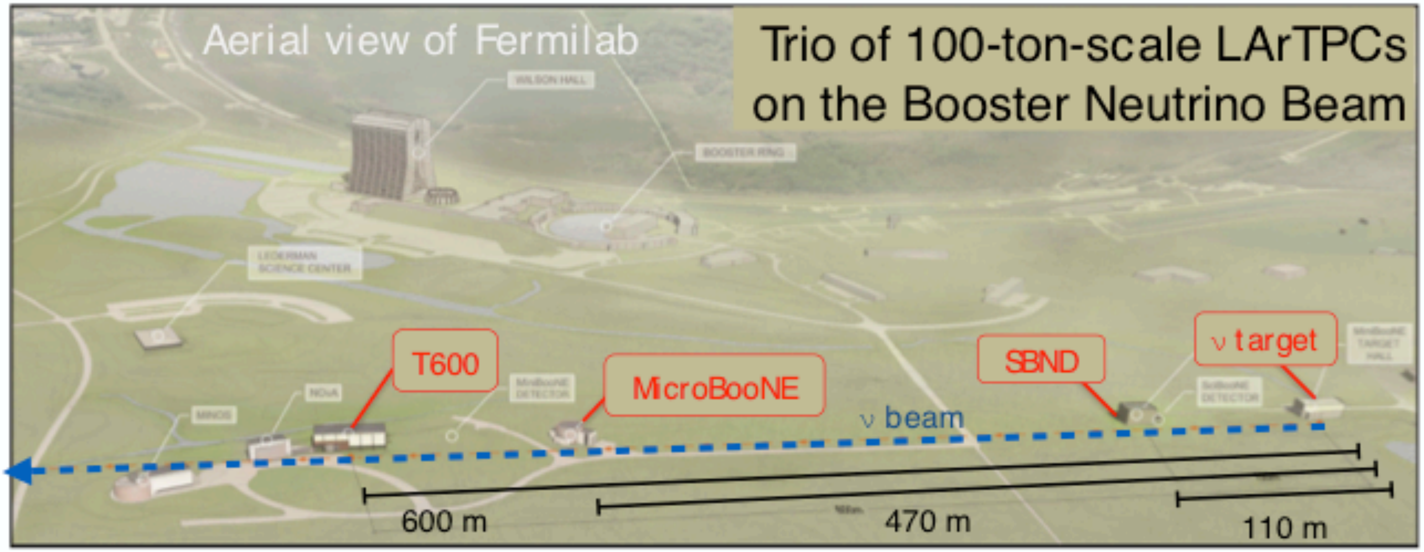
Neutrinos & the Dark Sector
(Daniele Alves & Patrick deNiverville)

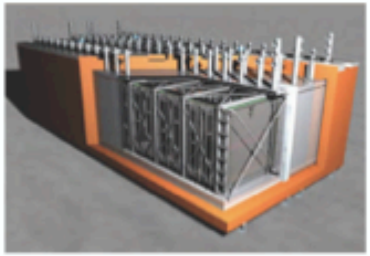
- Oscillation probabilities can be enhanced for specific windows of neutrino energy and medium density
  - could provide explanation for excess of low energy electron-neutrinos observed by MiniBooNE
  - does not affect of MSW matter effect in the Sun



Short Baseline Neutrino (SBN) Program

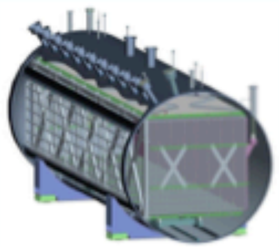
See talk by D. Schmitz





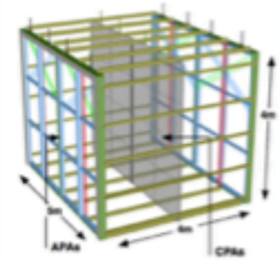
ICARUS-T600

476 tons



MicroBooNE

89 tons

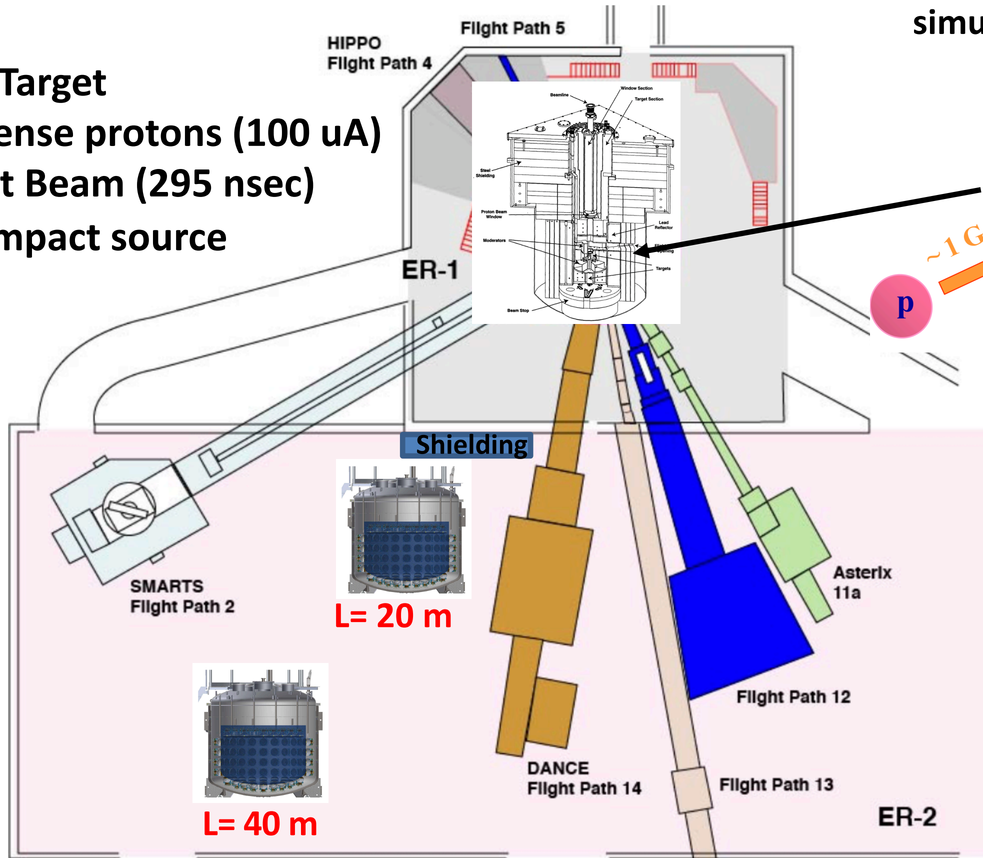


Short Baseline Near Detector (SBND)

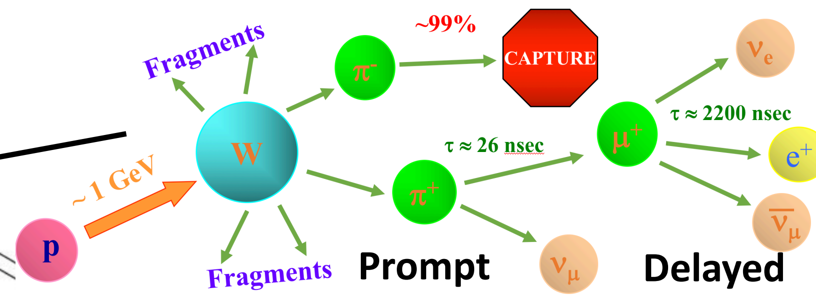
112 tons

CCM Experiment at Lujan

Lujan Target
- Intense protons (100 uA)
- Fast Beam (295 nsec)
- Compact source



Intense source muon neutrinos: target MCNP simulation flux 4.74x10^5 nu/cm^2/s at 20 m (slide 52)



Lujan Experimental Area
- Space for large 10-ton liquid Argon neutrino detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

Conclusion

• The results from LSND & MiniBooNE and the other anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile neutrinos and new dark sector particles and interactions.

• Sterile neutrinos & the new dark sector particles would contribute to the dark matter of the universe and would have a big impact on particle physics, nuclear physics, astrophysics and cosmology.

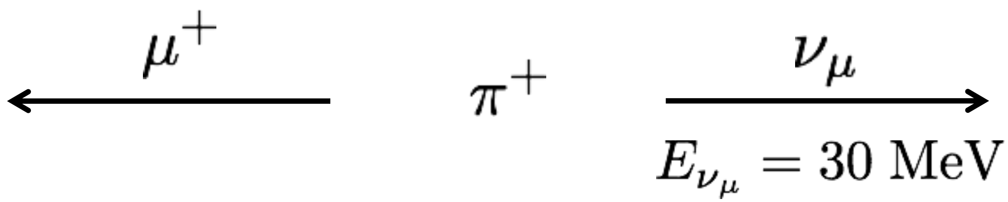
• Future experiments (e.g. SBN at Fermilab & CCM at Lujan) have the golden opportunity of proving whether sterile neutrinos and dark sector particles exist!

Backup

Coherent CAPTAIN-Mills (CCM) experiment

<u>Production mechanism:</u>

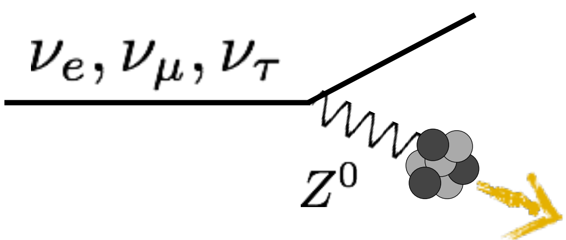
charged pions decaying at rest $\Rightarrow$ monoenergetic neutrinos



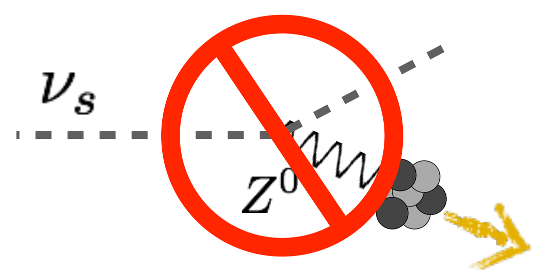
<u>Detection mechanism:</u>

Coherent Elastic Neutrino-Nucleus Scattering
"CEvNS"

present for all active neutrinos

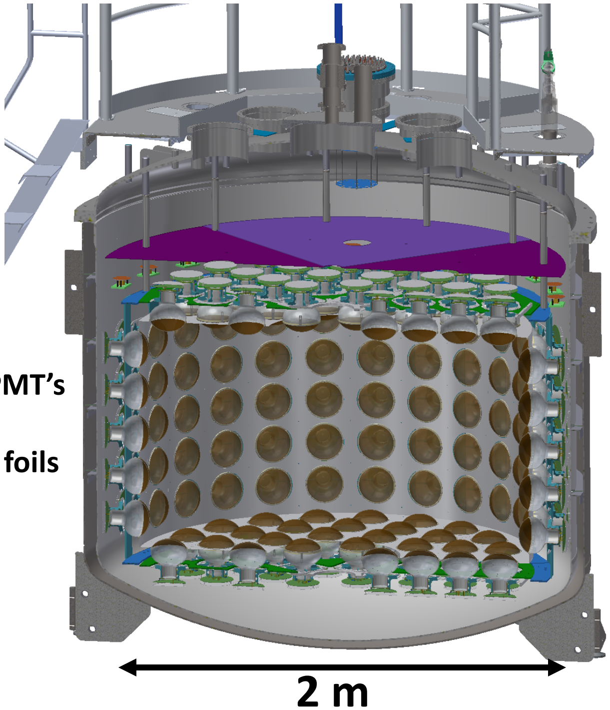


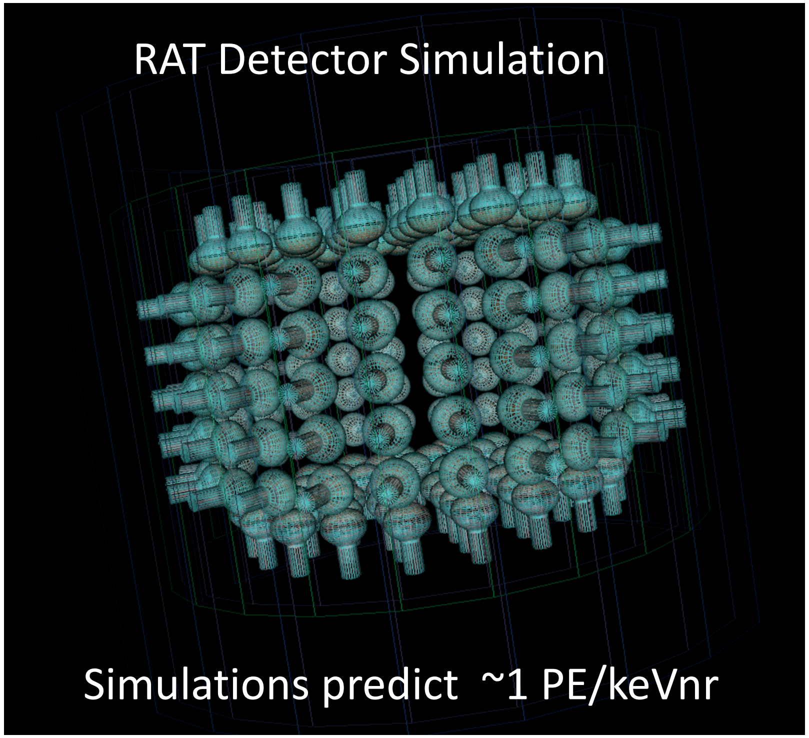
absent for sterile neutrinos



Detecting Coherent Neutrinos: Maximizing Scintillation Light Detection!

- **220 R5912 PMT’s**
- **wavelength shifting TPB foils**



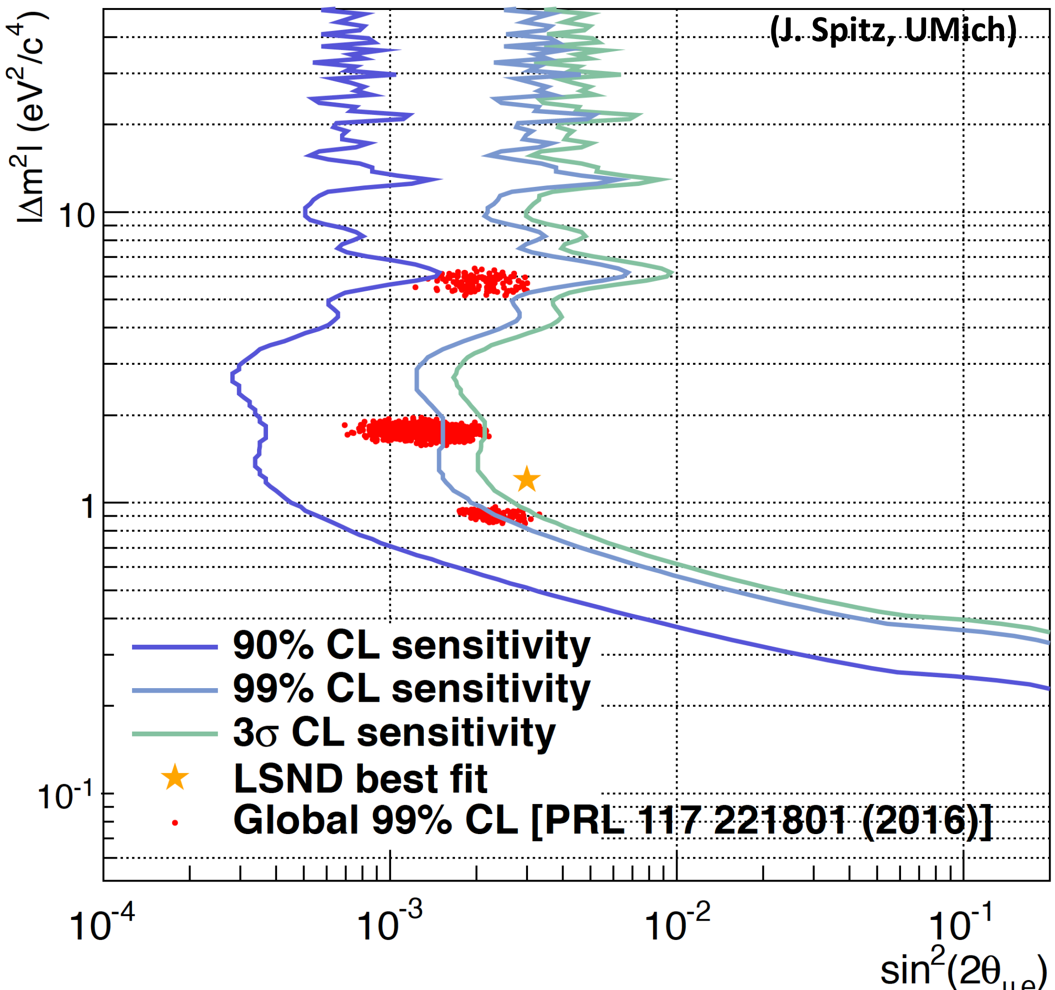


- Liquid Argon scintillates at 128 nm with 40 photon/keV
    - fast 6 nsec and slower ~1 usec time constants.
- **Detailed RAT/GEANT4 simulation predicts 10-20 keV detection threshold.**

- **CCM will also allow more tests of LAr scintillation light for SBN & DUNE.**

CCM Sensitivity

$\nu_\mu \to \nu_e$ Appearance



Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

- **Can prove/disprove at ~3σ LSND 3+1 sterile neutrino hypothesis.**
- **Five year run would approach 5σ!**
- **If no signal, can rule out world best fit at better than 90%**

Future Short-Baseline ν Experiments

- There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

- Accelerator ν Experiments: MicroBooNE+SBND+ICARUS, MINOS+, NOvA, DUNE, OscSNS at ORNL, CAPTAIN-Mills, JSNS^2 (J-PARC E56), IsoDAR, nuPRISM

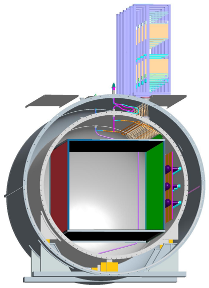
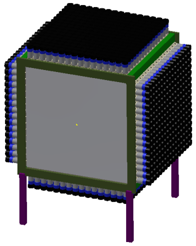
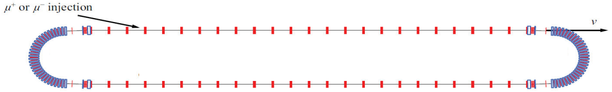


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

- Reactor ν Experiments: Neutrino-4 SOLID, PROSPECT, NEOS, DANSS

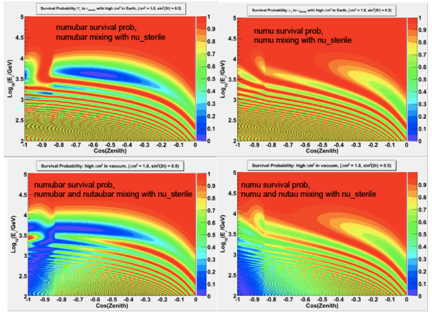


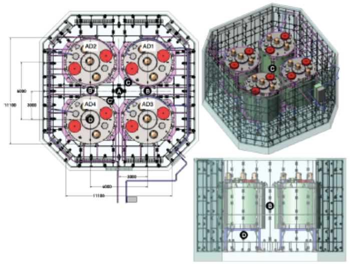


- Radioactive Source ν Experiments: BEST

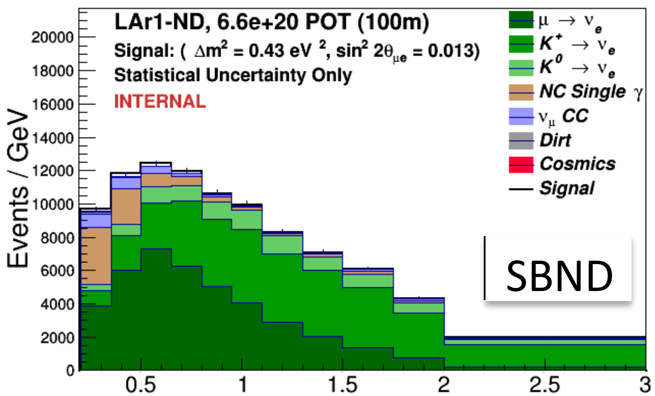
- Atmospheric ν Experiments: IceCube

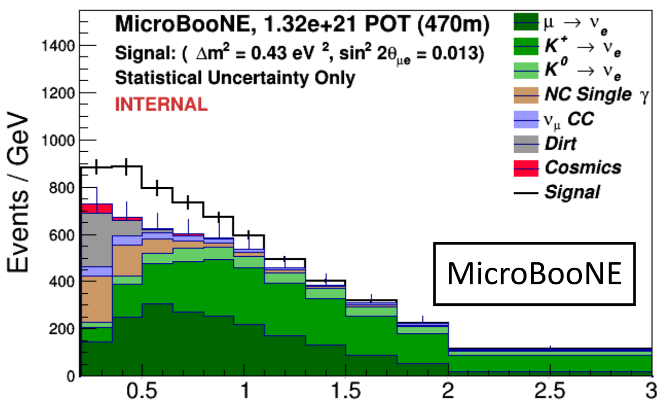
- Beta Decay & Double Beta Decay

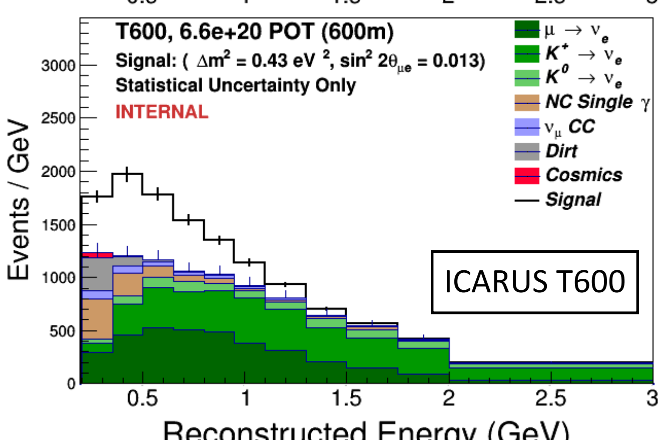


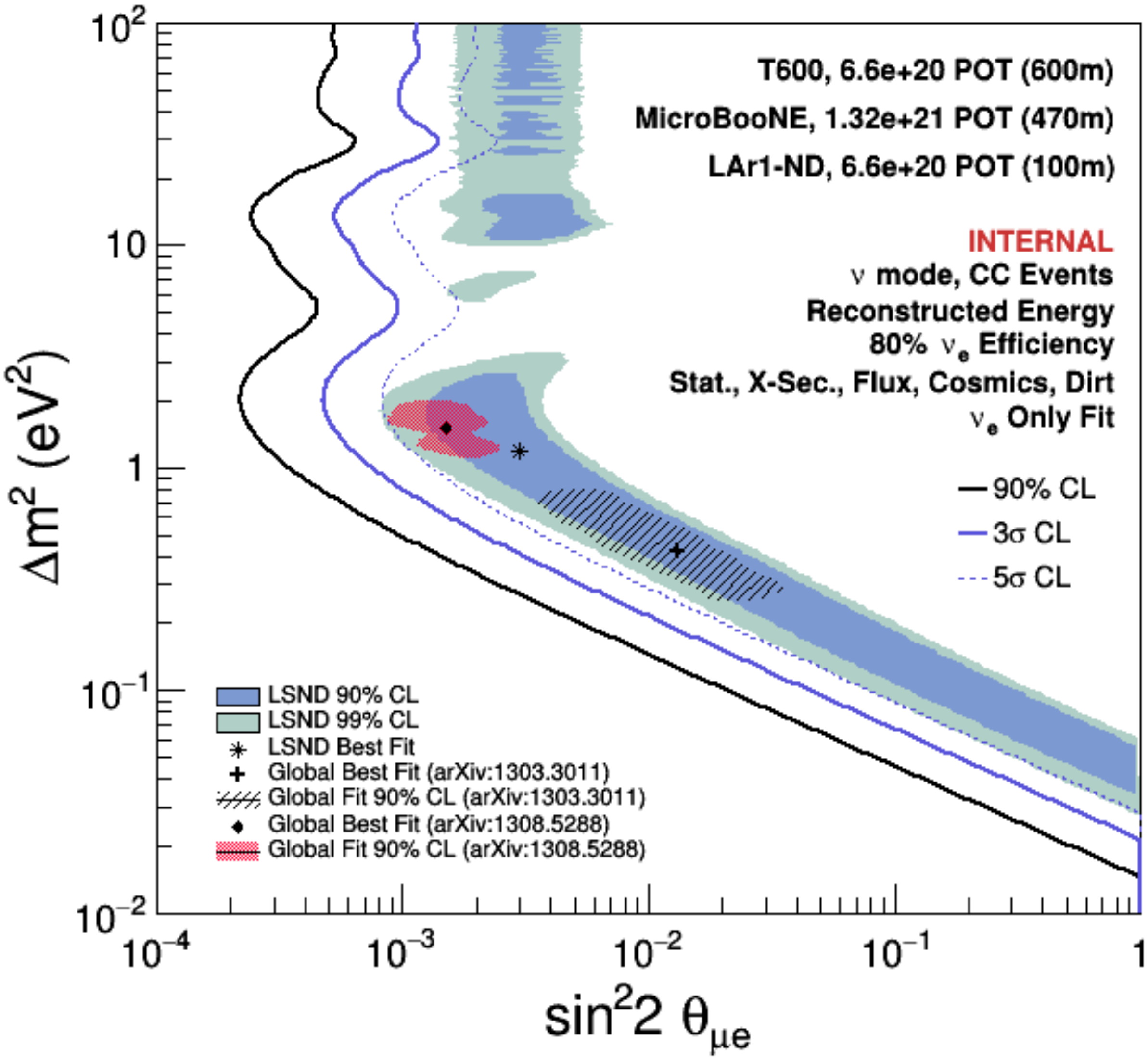


ν_e Appearance Sensitivity

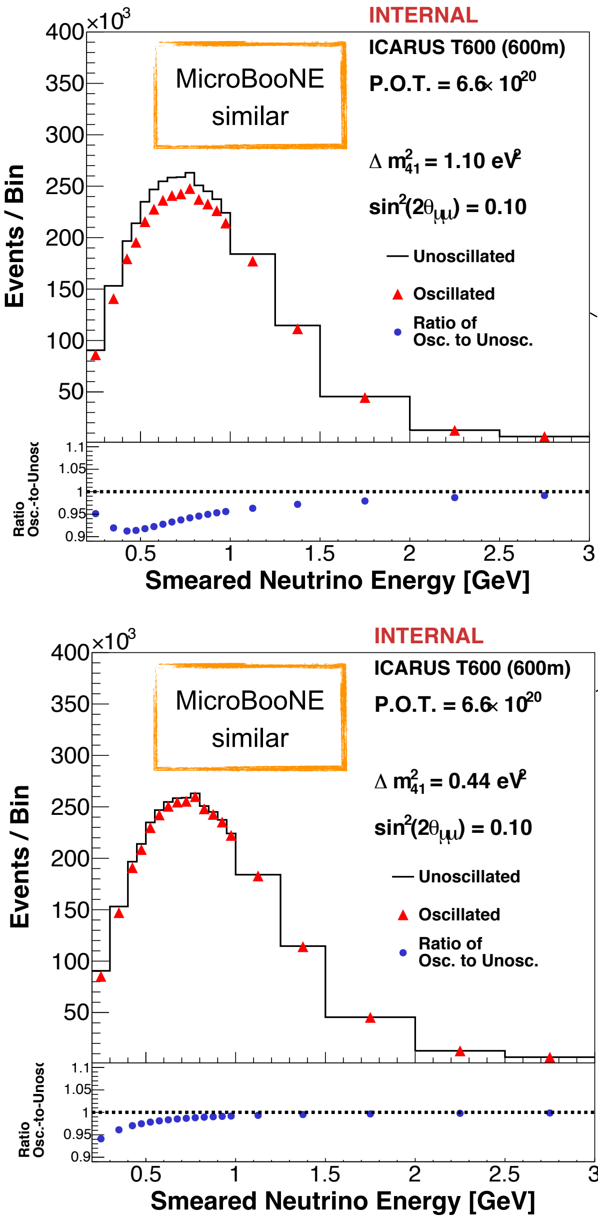


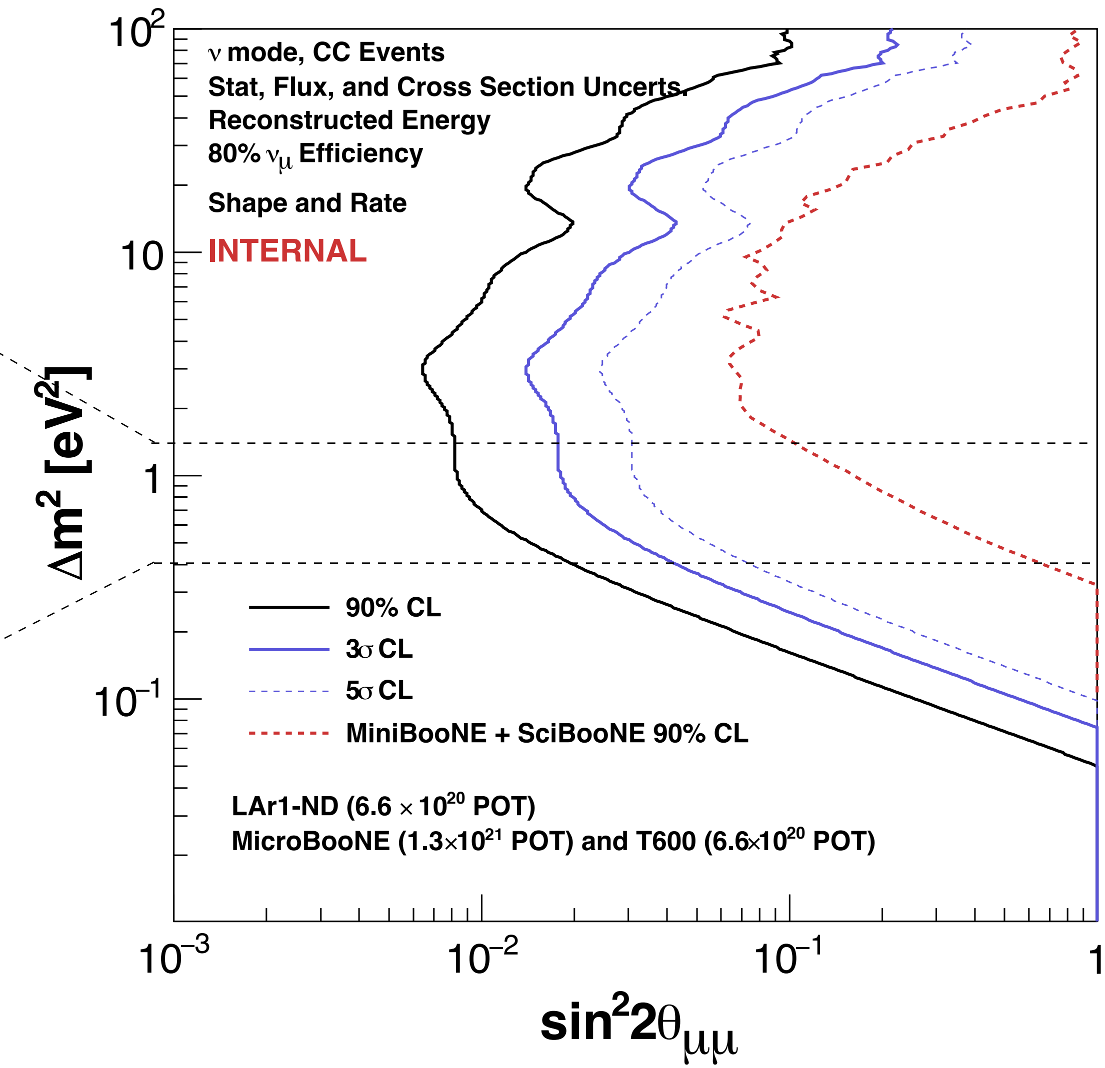






ν_μ Disappearance Sensitivity





Sensitivity includes full flux and cross section systematics, but not detector systematics at this time.

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \,|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}|\, \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As #ν increases, the formalism gets rapidly more complicated!

#ν	#Δm_{ij}^2	#θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim$ ¼ $P(\nu_\mu \rightarrow \nu_x)\, P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active
and the N heavy neutrinos are mostly sterile.

For 3+1 Models:
arXiv:1207.4765

$$P(\nu_\alpha \to \nu_\beta) \simeq 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)\ ,$$

$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - 4(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)\ .$$

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

For 3+2 Models:
arXiv:1207.4765

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) \simeq & -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} \sin^2(1.27\Delta m_{54}^2 L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin^2(1.27\Delta m_{41}^2 L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} + |U_{\alpha 5}||U_{\beta 5}|)|U_{\alpha 5}||U_{\beta 5}| \sin^2(1.27\Delta m_{51}^2 L/E) \\
& +2|U_{\beta 5}||U_{\alpha 5}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{54} \sin(2.53\Delta m_{54}^2 L/E) \\
& +2(|U_{\alpha 5}||U_{\beta 5}| \sin\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin(2.53\Delta m_{41}^2 L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{54})|U_{\alpha 5}||U_{\beta 5}| \sin(2.53\Delta m_{51}^2 L/E)\ ,
\end{aligned}
$$

ϕ_{54} is the CP Phase angle

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\alpha) \simeq & \ 1 - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2(1.27\Delta m_{54}^2 L/E) \\
& -4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E) \\
& +|U_{\alpha 5}|^2 \sin^2(1.27\Delta m_{51}^2 L/E))\ .
\end{aligned}
$$